U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-270 086

EPA's Stationary Source Combustion Control Technology Program - FY 1976

Acurex Corp, Mountain View, Calif Aerotherm Div

Prepared for

Industrial Environmental Research Lab, Research Triangle Park, N C

Jul 77

PB 270 086

EPA

EPA 600/7-77-077
July 1977

EPA's STATIONARY SOURCE COMBUSTION CONTROL TECHNOLOGY PROGRAM--FY 1976

Interagency
Energy/Environment
Research and Development
Program Report

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SPRINGFIELD, VA. 22161

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TECHNICAL REPORT DATA

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1. REPORT NO. EPA-600/7-77-077	2.
3. RECIPIENT'S ACCESSION NO.	
4. TITLE AND SUBTITLE: EPA's Stationary Source Combustion Control Technology Program--FY 1976	5. REPORT DATE: July 1977
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S): NA	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Acurex Corporation/Aerotherm Division 485 Clyde Avenue Mountain View, California 94042	10. PROGRAM ELEMENT NO. EHE624A
	11. CONTRACT/GRANT NO. 68-03-2160
12. SPONSORING AGENCY NAME AND ADDRESS: EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED: Task Final; Fiscal Year 1976
	14. SPONSORING AGENCY CODE: EPA/600/15

15. SUPPLEMENTARY NOTES: IERL-RTP project officer for this report is Joshua S. Bowen, Mail Drop 65, 919/541-2470.

16. ABSTRACT: The report summarizes the objectives, highlights, and accomplishments of EPA's research and development program for characterization, assessment, and control of the environmental impact of stationary combustion processes and energy conversion technologies. The combustion control program emphasizes the development and assessment of combustion modifications and control techniques which will have practical and economical application for controlling multimedia pollutants from a wide variety of combustion equipment categories. Although the major emphasis has been directed to the control of nitrogen oxides, the effort also addresses the reduction of other combustion-generated pollutants while maximizing system efficiency and energy conservation. EPA's combustion control program utilizes the talents and experience of a variety of contractors in combination with a limited number of inhouse projects. The cooperation and input of the industrial and academic sector has been very effective in achieving a high degree of credibility for the technical results. Major benefits of the program include improvement of the environment, particularly of air quality, and enhancement of the nation's energy posture, by providing greater flexibility for the use of coal as a major energy source.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution, Nitrogen Oxides Combustion, Combustion Chambers Fuels, Assessments, Field Tests Utilities, Boilers, Industrial Processes Stationary Engines, Catalysis, Heating	Air Pollution Control Stationary Sources Combustion Modification Environmental Assessment Catalytic Combustion	13B 07B 21B 21D 14B 13A 13H 21G 07D

18. DISTRIBUTION STATEMENT: Unlimited	19. SECURITY CLASS (This Report): Unclassified	21. NO. OF PAGES: 84
	20. SECURITY CLASS (This page): Unclassified	22. PRICE: $5.25 PC $4.50 MF

EPA Form 2220-1 (9-73)

EPA-600/7-77-077
July 1977

EPA's STATIONARY SOURCE COMBUSTION CONTROL TECHNOLOGY PROGRAM--FY 1976

by

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485 Clyde Avenue
Mountain View, California 94042

Contract No. 68-02-2160
Program Element No. EHE624A

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Research Triangle Park, N.C. 27711

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, D.C. 20460

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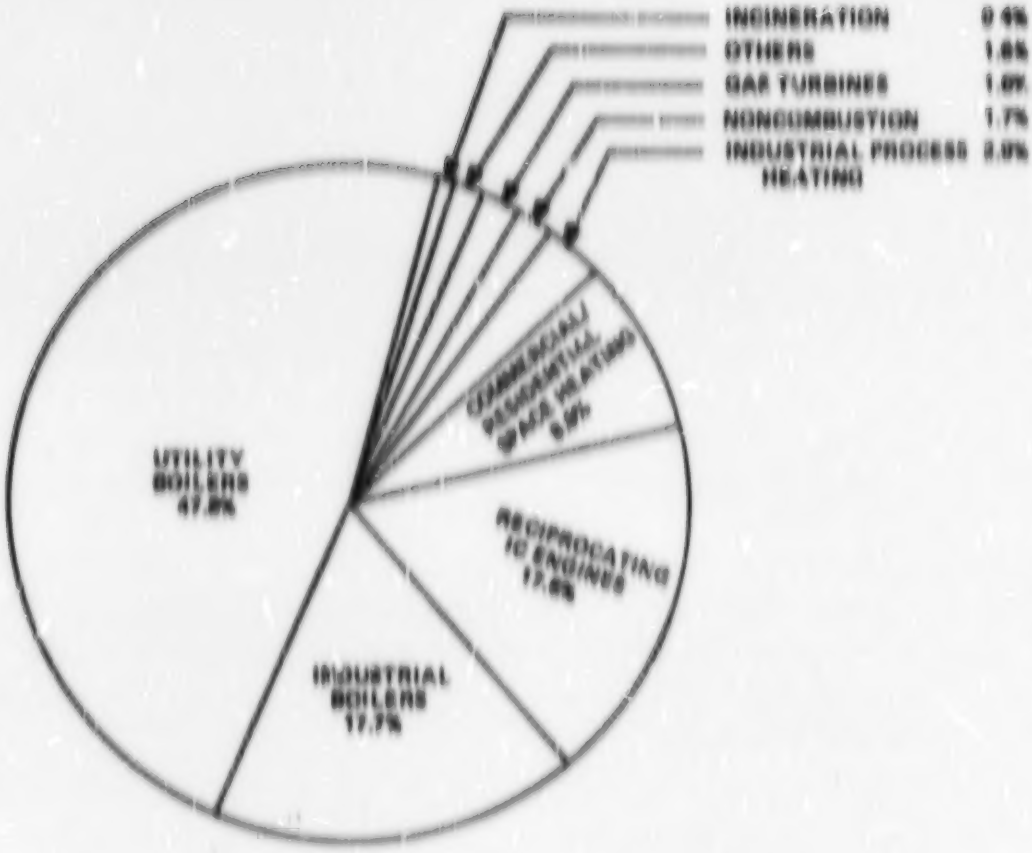
SECTION 1

INTRODUCTION

This report presents the highlights and accomplishments of the Combustion Research Branch (CRB), Industrial and Environmental Research Laboratory, Research Triangle Park (IERL-RTP) for the calendar year 1976. The objective of the CRB is the characterization, assessment, and control of the environmental impact of energy conversion technologies. Programs are underway to identify the multimedia pollution problems associated with combustion processes (i.e., related to residential, commercial, industrial, and utility boilers, industrial process combustion equipment, and stationary gas turbine and reciprocating IC engines) utilizing conventional fossil and alternate new fuels.

The major goals of these efforts are the development and demonstration of combustion modifications and control techniques or devices to prevent or minimize pollution problems for these processes in a cost-effective, energy-conserving, process-efficient, and environmentally acceptable manner. Although the major emphasis of the program is on investigation of technology for control of oxides of nitrogen (NO_x), efforts are also underway to reduce or eliminate other pollutants (such as hydrocarbons, carbon particulate, smoke, carbon monoxide, and various potentially hazardous trace and minor species) while simultaneously maximizing system efficiency by optimizing system design and operating characteristics.

Combustion sources contribute about 98 percent of the total NO_x emissions from stationary sources. Some NO_x is formed in all fossil fuel combustion processes. Recent estimates of NO_x emissions from major source categories in 1974 are shown in the following figure. Control technology development studies indicate that combustion modification is the primary near-term method of controlling NO_x emissions from the combustion of fossil fuels.



ESTIMATED NO_x EMISSIONS

SOURCE	TONS/year
UTILITY BOILERS	5,814,000
INDUSTRIAL BOILERS	2,153,000
RECIPROCATING IC ENGINES	2,140,000
COMMERCIAL/RESIDENTIAL HEATING	1,069,000
INDUSTRIAL PROCESS HEATING	350,000
NONCOMBUSTION	224,000
GAS TURBINES	190,000
INCINERATION	45,400
OTHER	192,000
TOTAL	12,176,400

Summary of 1974 stationary source NO_x emissions

Following provisions of the 1970 Clean Air Act amendments, the EPA, in 1971, promulgated a primary and secondary National Ambient Air Quality Standard (NAAQS) for NO_2 of 100 $\mu g/m^3$ (annual average). The EPA NO_x abatement strategy to achieve and maintain the NAAQS focused on 90 percent reduction of NO_x emissions from light duty vehicles by 1976 as mandated by the Clean Air Act. Stationary sources were to be regulated through the application of reasonably available control technology under the Federal Standards of Performance for New Stationary Sources and, where required, under the State Implementation Plans for existing sources. The sufficiency of EPA's ongoing stationary source NO_x control development program to meet the needs of the NO_x abatement strategy was contingent upon the implementation of the statutory standard of 0.25 mg NO_2/m (0.4 g NO_2/mile) for light duty vehicles.

Until recently, it appeared that existing or a low level of development of stationary source control technology would be adequate to achieve and maintain air quality in the 1980 to 2000 period. However, since 1973, the energy shortage and changes in the national NO_x abatement strategy have placed additional demands on the stationary source control technology. Specifically, consideration must now be given to the following factors:

- Decreased reliance on mobile source emission reductions
- Increased awareness of potential multimedia environmental impacts from stationary source combustion and NO_x controls
- Recognition of the need for advanced stationary source controls to account for energy growth demands between 1980 and 2000
- Accelerated development of alternate fuels and combustion processes
- Extensive fuel switching to coal
- Increased fuel and equipment costs causing reassessment of economic and energy consumption trade-offs for various options

Present CRB activities to address the above needs are divided into the following elements: field testing and environmental assessment, process research and development, fuels research and development, and fundamental studies. Field testing is directed toward the determination of the

range of NO_x control possible in existing equipment, and environmental assessments identify the multimedia environmental impact of stationary combustion sources and NO_x control systems for attainment and maintenance of current and projected air quality standards. Process R&D encompasses the development and demonstration of optimum NO_x control technology for existing and new combustion systems. Fuels R&D studies are designed to develop generalized combustion control technology which is applicable to the control of NO_x and other pollutant emissions from the combustion of conventional fuels, waste fuels, and future fuels. Fundamental studies provide an understanding of important phenomena in the formation and destruction of pollutants during combustion which may then be utilized in pilot scale equipment and fuels control technology.

The following section presents a general program overview and the final section summarizes current activities of the Combustion Research Branch in the above research categories. A program funding summary is provided in Appendix A, and a tabulation of EPA reports relating to NO_x combustion control is presented in Appendix B.

SECTION 2

PROGRAM OVERVIEW

Nitrogen oxides (NO_x) are among the atmospheric pollutants for which standards and regulatory controls have been enacted by both the EPA and state and local agencies. The regulations result from the quantity of NO_x emitted by both mobile and stationary sources and from the recognition of the potential for widespread adverse public health and welfare effects. Atmospheric NO_x emissions undergo complex photochemical reactions in combination with selected hydrocarbons and sulfur oxides to form precursor species of smog and other deleterious substances.

2.1 PROGRAM RATIONALE

Stationary sources account for over half of the total man-made NO_x emissions annually, and of the stationary source emissions, fuel combustion is responsible for over 98 percent. Combustion generated NO_x emissions result from both thermal fixation of nitrogen in the combustion air (thermal NO_x) and conversion of fuel bound nitrogen (fuel NO_x). Thermal NO_x is formed through a series of reactions which are strongly dependent on local flame temperature and less dependent on oxygen availability. Fuel NO_x is formed by the oxidation of organic nitrogen compounds through a series of reactions strongly dependent on local oxygen availability and to a lesser extent, on temperature. Thus, NO_x emissions can be strongly affected by nitrogen containing fuels such as coal. Recent trends toward the use of coal as a primary fuel have placed greater emphasis on NO_x control technology. The Esso R&E (Exxon) study of 1969 and subsequent updates identified combustion process modification as the most efficient as well as the most cost-effective means of reducing combustion generated NO_x emissions from stationary sources. CRB's combustion process modification activities

are accordingly directed toward the characterization, assessment and control of combustion generated air pollution, with particular emphasis on NO_x.

2.2 PROGRAM OBJECTIVES

The overall objective of the CRB's NO_x combustion modification program contributes to the overall goal of the IERL which is the development and demonstration of cost-effective technologies to prevent, control, or abate pollution from operations with multimedia environmental impacts associated with the extraction, processing, conversion, and utilization of energy and mineral resources. Further objectives are the identification and evaluation of environmental control alternatives of those operations as well as the assessment of associated environmental impacts. The overall IERL-RTP goal in stationary source air pollution control development can be divided into four specific objectives:

- To describe at least one method for control of each major source of pollution
- To provide a technical base for EPA's enforcement activities
- To establish technical and economic data to support New Source Performance Standards (NSPS)
- To provide information required to make environmentally sound decisions on energy development policy

2.3 APPROACH

IERL-RTP's combustion modification activities relating to NO_x and other combustion generated pollutant control work within the following framework:

- NO_x Environmental Assessment/Applications Testing - determination of the environmental emissions of NO_x and other combustion related pollutants from stationary combustion sources. Evaluation of the environmental effectiveness and impact (as compared to the uncontrolled state) of combustion control modifications

including alternative operating conditions, minor retrofit control, extensive retrofit control for existing units, and optimized design for new units, or selection of an alternate low-NO_x process.

- Development of Combustion Modification Technology for NO_x - development and demonstration of practical combustion modification technology for controlling NO_x and related combustion generated pollutants from utility boilers, commercial boilers, industrial boilers, residential heating systems, industrial combustion equipment, stationary engines, and advanced processes.

Since over 90 percent of the NO_x emissions from stationary sources are formed during the combustion of fuels, the logical approach to control is the modification of the conditions under which fuel combustion takes place. The techniques which can be used are now well documented and, depending on a variety of factors, offer potential for substantial control of NO_x (50 to 90-plus percent). In addition, these techniques can be optimized to reduce or eliminate emissions of other pollutants (such as CO, hydrocarbons and carbon particulate) and to increase system efficiency by careful attention to system design and operating characteristics.

This approach to control NO_x builds on a solid technology base for conventional fossil fuels and provides for the further generation of new technology for both conventional and alternate fuels. The emphasis is on source-specific field application of control techniques ranging from minor hardware changes on existing sources to establish short-term control technology to complete system redesign for optimizing all energy and emission aspects of an equipment class. The field application studies are supported and guided by activities in: generalized burner and control system development, advanced process development based on novel concepts, evaluation of emissions aspects of alternate fuels, and fundamental and analytical research.

Field application of techniques for many optimized conventional fossil fuel combustion systems will be completed by the early 1980s, and design criteria for alternate fuels and advanced systems will be developed and partially demonstrated by that time. Due to lags between development

and application of technology attributable to normal scheduling and logistic considerations, it can be expected that field application of concepts in the latter class will be accomplished between 1980 and 1985. In carrying out this program, a combination of numerous contract, research grant, interagency, and in-house projects are being undertaken.

5.4 PROGRAM BENEFITS

Several far-reaching benefits will result from the NO_x combustion modification/control program on a near- and long-term basis.

The primary benefit of the program will be an improvement in air quality which is directly affected by NO_x emissions. Several indirect benefits will be realized as a result of improved air quality. Decreased health effects, such as respiratory diseases which have been related, either directly or indirectly, to air pollution rank as the primary indirect benefits.

The second major benefit will be the impact upon national energy supplies. Presently, the trend toward nationally abundant coal has been retarded, in part, as a result of nonexistent, uneconomical, or inadequate pollution controls. Successful combustion modification techniques will allow increased flexibility for the use of coal as a major source of energy. Further still, two secondary benefits derived from combustion modifications are the potential reduction of the emissions of other undesirable pollutants and a potential increase in system efficiency.

A third major benefit again relates to the national energy picture. Successful combustion control development will result in a further increase in the use of coal as a fuel for stationary sources allowing the cleaner fuels to be used for applications where control is less feasible. This is particularly true for mobile sources where the difficulties of pollution control technology have required the continued use of gasoline and diesel fuel.

SECTION 3
CURRENT PROGRAM STATUS

The present NO_x combustion modification program at the Combustion Research Branch can be divided into four major elements:

- Field Testing and Environmental Assessment
- Process Research and Development
- Fuels Research and Development
- Fundamental Studies.

A further element of the program is the efficient dissemination of technical information from its research activities to control developers, equipment manufacturers and users, and the authorities involved in setting and enforcing standards. Two practices have been initiated to establish an efficient means of technology transfer: (1) Symposia and (2) "Newsletters".

The first symposium on Stationary Source Combustion took place in Atlanta in September 1975, and the next meeting is scheduled for New Orleans for August 29 through September 1, 1977. Sessions were held in the key program areas of the CRB. The Fundamental Research session highlighted results from ten analytical and experimental studies of pollutant formation and reduction and concluded with a panel discussion on "Combustion Chemistry and Modeling". Developments in external combustion control, burner modifications, combustion of alternate fuels and alternate combustion concepts were presented in the Fuels Research and Development session. The Process Research and Development session highlighted development of advanced NO_x control technology through minor hardware changes to existing equipment which will provide guidelines for low NO_x new unit design and for retrofit field implementation of NO_x controls. The final session, Field Testing and Survey, contained seven papers on uncontrolled emission characterization and on

control achieved by alteration of operating conditions. The proceedings of the Atlanta meeting have recently been published as an EPA report.

The first issue of a "newsletter," entitled "NO_x Control Review," was published in March 1976. Issued approximately quarterly, the Review presents the status of stationary source NO_x control technology and related topics. Each issue leads off with major recent developments or topics of general interest; the remainder is divided into the following topical categories: control R&D, control implementation, alternate processes, flue gas treatment, regulatory strategies, technical briefs, recent publications, and a calendar of upcoming meetings. Future issues will include a listing of applications of NO_x control technology to major utility and industrial stationary combustion sources.

3.1 FIELD TESTING AND ENVIRONMENTAL ASSESSMENT

The field testing element includes studies designed to determine the potential for control of NO_x emissions from existing equipment. This work is generally performed by R&D organizations familiar with the specific combustion systems being studied, and with the financial and technical assistance of manufacturers, users, and trade associations. The field testing and survey studies are the initial efforts in the development of control technology and are designed to demonstrate the state of the art in control of NO_x and combustible emissions. In addition to developing trends and providing application guidelines for industry to minimize emissions with present technology, the work also suggests where R&D efforts should be concentrated by developing emission factors as a function of equipment type and size, and fuel consumed.

The environmental assessment component of the program element focuses on identification of the multimedia environmental impact of stationary combustion sources and NO_x controls and, for this impact, identifies the most cost-effective, environmentally sound NO_x control systems for attainment and maintenance of current and projected NO_2 air quality standards. This activity provides program guidelines for development of NO_x controls sufficient to assure compliance (to the year 2000) with air quality standards in critical air quality control regions.

3.1.1 Utility Boiler/Power Generation Equipment Field Testing

IERL-RTP's NO_x control program was initiated in 1970 when Exxon R&E began field testing utility boilers to define baseline emissions and establish the effect of combustion modification techniques. It was found that NO_x emissions from gas- and oil-fired boilers could be reduced by 50 to 60 percent by using combustion modification techniques such as low excess air firing, staged combustion, flue gas recirculation, load reduction, air preheat reduction, change in burner tilt, and change in primary to secondary air ratio. Of these, the first two were found to be most applicable and cost effective. Combustion modification with coal-fired boilers was less successful for NO_x reduction and more difficult because of operating problems. Since the Exxon systems study identified coal-fired utility boilers as the top ranking source of NO_x emissions from stationary sources, efforts were concentrated on these units. Further Exxon studies showed that reducing the excess air level and employing staged combustion, as with gas- and oil-fired boilers, resulted in significant NO_x reductions, averaging about 40 to 50 percent for the boilers tested. The degree of reduction, as well as baseline NO_x emission levels, varied with the design and size of coal-fired boilers tested and with coal type. No extreme differences in flue gas particulate loadings and in the carbon content of the flyash were found during the boiler tests.

A subsequent extension to the Exxon field test program of utility power generation equipment includes trace specie emission measurements and testing of an additional six units including a carefully controlled investigation into the effects of NO_x controls on tube wastage in coal-fired boilers. Emission measurements will be made of sulfates, nitrates, HCN, HCl, POM's, and PCB in addition to the original NO, NO_2, SO_2, SO_3, CO, CO_2, O_2, UHC, particle loading, and particle size distribution. The additional test sites extend previous emission characterizations and control tests to a broader range of design types and operating conditions. Corrosion tests will be conducted on a 500 MW horizontally-opposed, dry-bottom coal-fired boiler with an initial 4-month baseline test to establish normal tube wastage rates followed by a 6-month run in which low NO_x conditions will be accomplished through low excess air firing and staged combustion via burners out of service. The tests will use a new ultrasonic tube thickness sensor (accurate to ± 0.0001 inch),

corrosion coupon probes, and replaceable tube wall panels with before and after metallographic characterization.

A new program is being initiated to conduct long-term comprehensive emissions and corrosion tests on coal-fired utility boilers designed to meet the New Source Performance Standards for NO_x of 301 ng NO_2/J (0.7 lb NO_2/10^6 Btu) heat input. Each test boiler will exceed 125 MW in capacity and burn high sulfur bituminous coal. It is expected that these tests will fully quantify the effects of NO_x combustion modification on emissions, corrosion, boiler performance, and reliability for major coal-fired boiler design types.

Future work with utility boilers will continue to concentrate on coal-fired units, but will also consider firing of mixed fossil fuels (e.g., coal and oil, or gas and oil) fired simultaneously, coal-derived fuels (e.g., low-Btu gas and solvent refined coal), and waste fuels. Tests are also underway with other power generation equipment such as gas turbines and large internal combustion engines.

3.1.2 Field Testing of Industrial Boilers

In 1973, a major field test program with industrial boilers was initiated. KVB Engineering was awarded a contract to test approximately 50 gas-, oil-, and coal-fired boilers, ranging in size from 10,000 to 500,000 pounds of steam per hour during the first year. Measurements included efficiency and emissions of NO_x, SO_x, HC, CO, smoke, and particulate mass. The tests were short-term and concentrated on operating variables such as excess air, load, swirl adjustment, and primary, secondary, and tertiary air adjustment. During the second year, 18 boilers were tested in more detail with more extensive modifications, such as overfire air, flue gas recirculation, and variable air preheat temperature. Also, particle size distribution and (on approximately five oil- and coal-fired boilers) trace specie emissions were measured. The 2-year study provided the following data on uncontrolled baseline emissions: 164-922 ppm, 65-619 ppm and 50-375 ppm for coal, oil and gas firing, respectively. Corresponding baseline operation emission averages were 275 ppm, 120 ppm, 293 ppm, 269 ppm and 139 ppm for coal, #2 oil, #5 oil, #6 oil, and natural gas. Excess air, burners out-of-service and flue gas recirculation proved to be the most effective combustion modification techniques for

reduction of NO_x emissions without sacrificing boiler efficiency. NO_x reductions up to 35 percent without increases in particulate emissions were experienced with low excess air firing. Flue gas recirculation reduced NO_x by 10 to 40 percent, but increased particulate by 5 percent and boiler efficiency was slightly reduced. The burners out of service technique reduced NO_x up to 54 percent without reduction in efficiency, but particulate emissions always increased. A final report was recently completed on the second phase of this project, and the study will culminate in the issuance of instructional guidelines for low emission operation and design of industrial boilers.

3.1.3 Field Testing of Industrial Process Equipment

IERL-RTP has contracted with KVB to conduct a 1-year field test program for industrial process equipment, gas turbines, and internal combustion engines. Emphasis is on detailed emission characterization of a representative group of furnaces, kilns, ovens, and dryers, firing coal, oil, gas, waste fuel, and mixed fuels. Measurements will be made of NO, SO_2, SO_3, O_2, CO, CO_2, HC, particle size and grain loading, opacity, and where relevant, trace metallics and trace organics (POM, PCB). KVB will also assess the degree of emission control achievable from modification of operating parameters such as unit load, excess air, and combustion air preheat. The gas turbine tests will assess the use of water injection as a means of NO_x control. A total of 25 units will be tested.

3.1.4 Residential/Commercial Heating Systems Testing

In an IERL-RTP sponsored effort, Battelle has recently completed work on guidelines for residential and commercial oil burner adjustments. Intended for use by service managers for service training and by skilled service technicians in their oil burner service work, the adjustment guidelines are important because they ensure reliable automatic operation, provide for efficient fuel utilization and minimize air pollution. In addition, the guidelines also include appendices with background material on pollutants of primary concern, field-type instruments and significance of measurements, fuel oil characteristics, and emission characteristics of residential and commercial oil burners and boilers.

A pamphlet produced in-house entitled "Get the Most From Your Heating Oil Dollar - Servicing Cuts Cost and Pollution" is being distributed to homeowners throughout the U.S. It is designed to transfer emissions and fuel conservation technology developed during field tests of residential equipment directly to the public.

In-house studies closely related to the field testing are being conducted on emission characterization and design evaluation for commercial combustion systems. The objective of this work is to investigate, under controlled laboratory conditions, the emission performance of existing/prototype commercial combustion systems and components and to evaluate effects of new burner/combustor designs and modifications on the emission and energy efficiency performance. Two different equipment systems have been baselined; that is, the best conditions for minimum emissions with unaltered equipment have been established. These systems include two major types of firetube packaged boilers: Scotch marine and firebox.

The Scotch marine firetube boiler has been utilized for the study of two fuel-oil/water emulsion devices: The Cottell Ultrasonic Emulsifier and the Total Emulsifier. The Cottell device provided significant reductions in smoke number and particulate emissions. The Total device provided significant reductions in particulate when firing distillate-oil/water emulsions, but smoke increased because the particle size distribution shifted to a smaller size. Neither emulsifier reduced NO_x emissions significantly when firing residual oil (which has a high-fuel nitrogen content); however, a significant NO_x reduction was observed when distillate oil was fired. On-going tests on the Elf Union (a French oil company) emulsion burner with a capability of 10-70 gph capacity have not resulted in data as yet. Some emulsion devices may have a small potential for energy conservation by permitting boiler operation at lower excess air levels, but this may require trading back the emission improvements.

In addition to the basic emission characteristics, a number of design and equipment changes have been studied. A burner redesign program was successful in reducing CO, HC, and smoke emissions from the firebox/firetube package boiler without increasing NO_x emissions. A fuel injection equipment program has been carried out to determine emission characteristics from air, high pressure, and sonic atomization of No. 6 residual oil.

Seismic analysis of the Unit 1 auxiliary control equipment cabinets

A comprehensive sampling and analytical system for use on IERL-RTP in-house equipment facilities is being developed by Aerotherm and A. D. Little. The system consisting of a specialized source assessment stack sampler and a complete analytical chemistry lab, is presently in the design phase. Design completion is expected in late 1976 or early 1977.

3.1.5 Environmental Assessment and Systems Analysis of NO_x Combustion Modification Technology

A major contract award has been made to the Aerotherm Division of Acurex Corporation for a multimedia environmental assessment and system analysis of NO_x combustion modification techniques. This effort is to determine the technical soundness and environmental acceptability of these control methods, and to ensure that any deficiencies or potential problems are identified and corrected in a timely fashion, before the technologies are adopted commercially.

The general technical approach in this project is based on the need to provide efficient and timely assessments of near-term control technologies while maintaining a comprehensive treatment of likely control needs to the year 2000. Throughout the program, emphasis will be given to synthesis of existing and emerging technology on control systems, trace emission and pollutant transport transformation and impact. The major project effort will go toward the compilation and evaluation of data from past and ongoing programs for the EPA and other agencies. Additionally, the environmental assessment activities will be coordinated with the IERL-RTP guidelines developed for the numerous ongoing source and environmental assessments. The evaluation of potential air quality standards and NO_x abatement strategies will be coordinated with the Office of Air Quality Planning and Standards (OAQPS) as well as the several task forces established to define mobile source emission control needs. The intent of this evaluation is to obtain an objective overview of the future needs for combustion modification NO_x controls.

The approach and level of effort allocated to project tasks is based on prioritization of sources, controls, pollutants, and Air Quality Control Regions (AQCR). The basis of the prioritization is to focus the study on development needs for environmentally sound control systems. Throughout the program, emphasis will be given to those sources, controls and multimedia

impacts most likely to be involved in control implementation in critical AQCR's up to the year 2000. Early use of the systems analysis models will aid in setting the program priorities. A screening approach will be used in the systems analysis whereby a simple model will be used to prioritize the options. More sophisticated models will be introduced for verification as process and emission data become available.

The effort will be time-phased on a descending priority basis with early emphasis on near-term sources and controls. Subsequent updates will be made to maintain a current assessment of the high priority areas. This approach requires parallel initiation of all program elements with early emphasis on gathering results from previous efforts and later emphasis on synthesis or generation of new data.

3.2 PROCESS R&D

IERL-RTP's process research and development work involves the application of optimum NO_x control technology to existing and new combustion systems. The results of these studies provide the basis for the demonstration of combustion control technology. During the past year, interest in projects in this area has continued to develop.

3.2.1 Combustion Modification for Utility Boilers

In a study being conducted by Combustion Engineering, Inc., a 400 MW tangential utility boiler equipped with factory-installed overfire air firing western bituminous "B" coal yielded NO_x emissions as low as 189 ng NO_2/J (0.44 lb NO_2/10^6 Btu), which is below the Standard of Performance for New Stationary Sources of 301 ng NO_2/J (0.7 lb NO_2/10^6 Btu). Baseline NO_x emissions for this unit, without the use of the overfire air system, ranged from 258 to 301 ng NO_2/J (0.6 to 0.7 lb NO_2/10^6 Btu) at normal excess air levels. Further tests evaluated the effect of total excess air, overfire air rates and tilts, burner tilt, wall slag and unit load. A 25 percent NO_x reduction from baseline was observed at normal, total excess air levels (25.2 percent) with the primary flame zone operated at 105 percent of stoichiometric. Slag buildup produced a negligible increase in NO_x under staged conditions. As with baseline conditions, NO_x increased with unit load. Carbon heat losses of 0.2 to 0.6 percent resulted during staging. This level corresponds

to the losses experienced under normal firing when operating below 15 percent excess air. Similar tests are now being conducted on a unit firing western sub-bituminous "C" coal. A final report on these two tests should be complete by late 1976.

Under an interagency agreement with IERL-RTP, TVA has evaluated biased firing on a 125-MW wall-coal-fired utility boiler. The tests indicate that a 30 to 50 percent NO_x reduction could be obtained for wall-coal-fired units depending upon load and burner configuration. Biased firing increases the carbon losses in the particulate causing a reduction in the ash conductivity which could affect ESP performance. The increases, however, were not deemed significant. Boiler efficiency is reduced over the entire load range under biased firing conditions. Data from 1 month tests using specially designed corrosion probes indicate accelerated tube wastage rates on the side walls, but the statistical significance of these results is currently in question.

Aerospace Corporation, under IERL-RTP sponsorship, has compiled and correlated field test data collected by the Los Angeles Department of Water and Power for some of their gas- and oil-fired utility boilers. A report on the extension of this effort to include coal-fired utility boilers is now in preparation. In addition to correlating emission data with combustion modification techniques, Aerospace has performed a combustion stability analysis to determine how a boiler can be redesigned to allow more flexibility in the use of combustion modifications. Aerospace is also generating a stationary source emissions inventory to the year 1975 and emissions projections to the year 1985. A final report has recently been completed.

Monsanto Research Corporation is currently preparing a report based on a study of utility and industrial coal-fired cyclone boilers. The objective of the study was to assess the need and the potential for controlling NO_x emissions from existing coal-fired cyclones. The final report will provide a population and geographic distribution with NO_x emission rates from several sources, as well as definition of available combustion modification techniques. Results will include projections of potential NO_x reduction through combustion process modifications and estimates of R&D costs to develop corresponding retrofit controls.

3.2.2 Combustion Modification for Industrial Boilers

KVB, under contract to IERL-RTP, tested 10 intermediate sized (10,000 -300,000 pph), pulverized coal and stoker fired boilers to determine the feasibility of substituting low sulfur western sub-bituminous coal for high sulfur eastern bituminous coal primarily as a means of reducing sulfur oxide emissions. The resulting impact on NO_x was also assessed. Major emphasis was placed on stoker units as pulverized coal units in this capacity range are less prevalent. Lower NO_x emissions were measured on both pulverized coal units and stokers as a result of the lower fuel nitrogen content of the coal and of the lower combustion temperatures due to the high moisture content of western coals. In general, the conversion of intermediate boilers to western coals was found to be a feasible alternative. Guidelines for conversion of a variety of design types to the use of western coals are in preparation.

A contract program will be initiated in late 1976 to study potential emission control technology for stoker coal fired industrial boilers. The program will focus on the complete spectrum of emissions from the sources and will develop technology to improve the environmental acceptability of stoker boilers. This contract will expand the prior work on small stokers to larger scale spreader stoker boilers and include a more comprehensive assessment of processed coals.

3.2.3 Combustion Modification for Residential/Commercial Heating Systems

Battelle, under contract to IERL-RTP, completed a technical assessment of increased utilization of stoker coal systems for residential and small commercial space heating applications. The assessment was based on (1) an experimental study evaluating emissions (including carcinogenic POM) from a 70 Hp boiler firing a variety of coals and processed fuel, (2) a survey to identify equipment and manufacturers, and (3) a survey to identify processes for the production of smokeless coals. The experimental research indicated that modifications in design and operation of small stoker boilers has potential for emissions reduction and, coupled with utilization of processed coals, could achieve improvements over existing equipment. However, the conclusion was made that current economic and environmental factors are unfavorable for increased utilization of coal in residential and small commercial applications.

3.2.4 Stationary Engine Combustion Technology

A program recently initiated with Pratt and Whitney Aircraft is directed toward the development of low NO_x gas turbine combustor technology. The study will focus primarily on dry control techniques because of fuel economy and operational considerations and will specifically address utility size (25 MW and larger) gas turbine units. Since future gas turbines may be required to burn heavier fuel oils or low-Btu gas containing significant levels of ammonia, the contract will also address control of NO_x resulting from the conversion of fuel nitrogen.

IERL-RTP has initiated an in-house investigation of stationary engine emissions control. Two engines have been installed at the RTP laboratory: a gas turbine and a precombustion chamber diesel. Experimental work to date has concentrated on the gas turbine with initial indications that CO, HC, and fine particulate emissions are serious problems in the unit. Determination of the baseline emission characteristics resulted in the NO_2 fraction of total NO_x ranging from 45 percent at no load to a negligible amount at rated load. The water/oil emulsion proved beneficial as a NO_x reduction technique with a 33 percent reduction in NO and total NO_x with a 26 percent addition of water. The water fraction is limited by the characteristics of the emulsion to about 35 percent. At water injection rates sufficient to appreciably reduce NO_x levels, CO levels could increase by as much as 20 percent over the lowest emission rates.

Tests on the precombustion chamber diesel engine have recently begun. The NO_x levels appear to be reduced by use of an oil/water emulsion, but data are still being analyzed. A catalytic muffler will be tested with the diesel in late 1976.

CRB is selecting a contractor for a new program in low NO_x IC engine development. The purpose of the new program is to investigate internal combustion engine chamber design parameters effects on air pollutant emissions. The goal is the development of a design giving substantial reductions in NO_x emissions for large bore stationary IC engines while maintaining or improving current technology levels for CO, HC, and carbon particulate emissions and fuel efficiency. Both new design and retrofit to existing engines will be considered; designs will be developed for gas-fueled spark ignition and oil fueled compression ignition 2- and 4-stroke engines.

Fig. 9 Side view of the test rig

Figure 4. Upper and lower coil assembly.

3.2.5 Industrial Process Equipment and Afterburners

The Institute of Gas Technology, under contract to IERL-RTP, has recently completed a survey of industrial process combustion. The objectives of the study were threefold: to identify the significant emission sources, to investigate the potential for effective emission controls, and to compile information on combustion equipment in use and future trends in process and equipment design. The iron and steel, cement, glass, aluminum and petroleum refining industries were identified as the major sources of combustion generated air pollution within the process combustion field. Recommendations were presented for NO_x control R&D programs for each of the significant processes within each industry.

A new program in 1976 will assess the pollution control and energy conservation potential of afterburner combustion systems. The primary objective of this study is to assess the environmental status of afterburner combustion systems and to develop guidelines for their application to minimize environmental problems. The program will completely analyze the problem of emissions from afterburner combustion systems and result in a standard of practice manual for applying these systems for emissions control without creating additional environmental problems.

3.2.6 Fluidized Bed Combustion Support

A contract has been awarded to Aerotherm for the design and construction of a fluidized bed combustion (FBC) sampling and analytical test rig. This small pilot-scale equipment will be installed and operated in IERL-RTP's in-house combustion research laboratory. This project is to provide for: comprehensive analyses of emissions from FBC, testing of alternative sampling and analytical procedures for FBC, and investigation of alternative add-on environmental control devices for FBC. Conceptual design has been completed, and installation and shakedown at IERL-RTP are scheduled for completion in mid-1977.

3.3 FUELS RESEARCH AND DEVELOPMENT

Fuels research and development studies are designed to develop generalized combustion control technology which is applicable to the control of NO_x and other pollutant emissions from the combustion of conventional fuels, waste fuels, and alternate new fuels. These studies are conducted on versatile experimental combustion systems with the specific purpose of developing combustion control technology for a specific fuel through single-burner design criteria or other combustion modification techniques.

3.3.1 Improved Burner/System Design

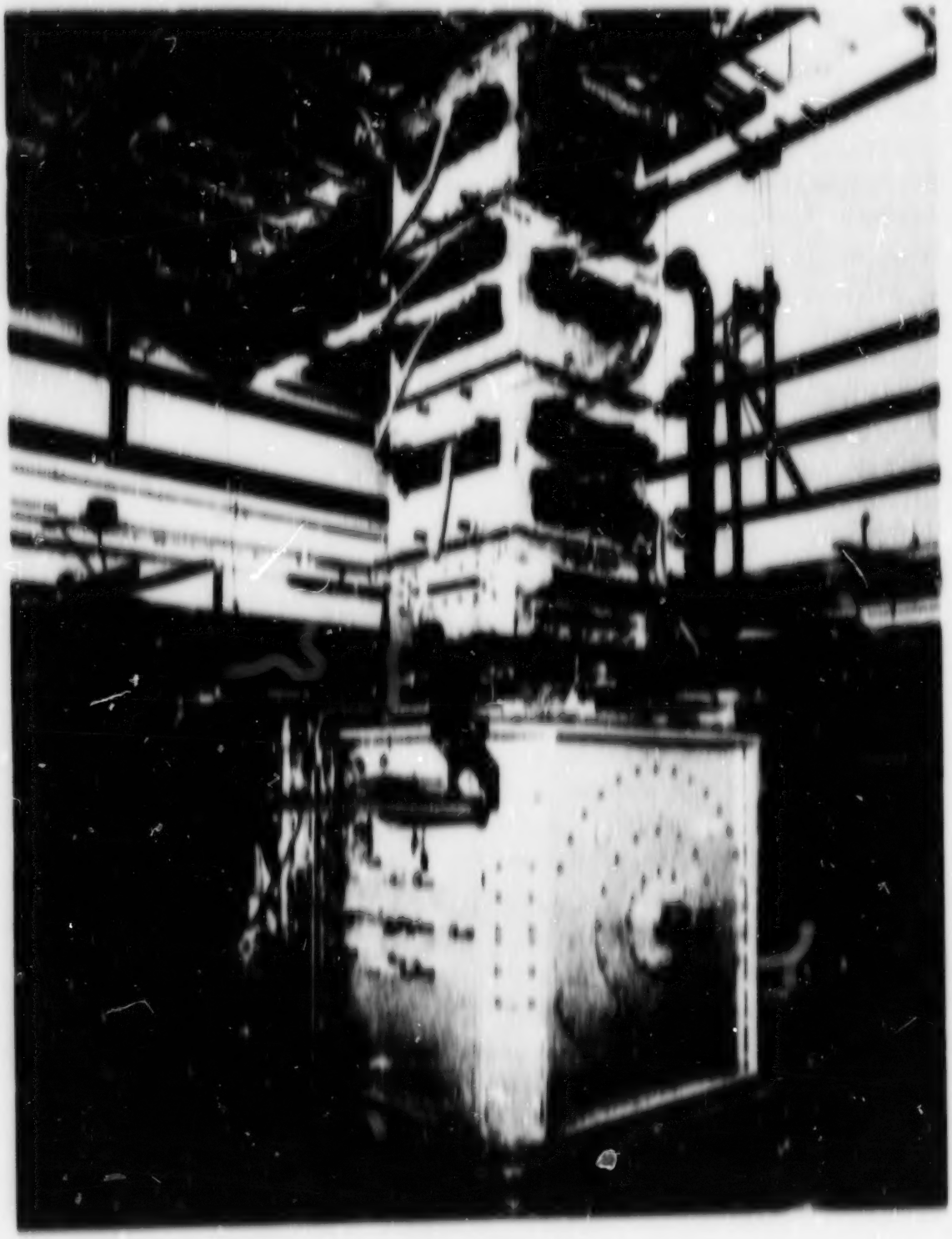
The Institute of Gas Technology has submitted a report on the investigation of the relationship between combustion aerodynamics and air pollutant emission characteristics of industrial gas burners firing natural gas. Three types of burners were studied: a scaled-down utility boiler burner, a kiln burner, and a baffle burner for steel reheat furnaces. The boiler burner showed NO_x reductions up to 91 percent with FGR. For the boiler burner, use of a 30-degree ring nozzle consistently produced lower levels of NO_x emissions than the 60-degree gun nozzle. For the kiln burner, NO_x emission reductions as high as 68 percent were demonstrated. The preferred approach was to modify burner parameters to yield the flame shape and length that will produce minimum NO_x emissions. For the baffle burner, external flue gas recirculation of 30 percent resulted in as high as 90 percent reduction in NO_x emissions. Present emphasis in this study is on the assessment of the emission characteristics of low Btu gases fired at ambient and elevated temperatures. Five gases are being investigated representative of the following industrial processes: Wellman Galusha-Air, Winkler-Air, Lurgi-Oxygen, Winkler-Oxygen, and Koppers Totzek-Oxygen. The overall objective of this program is to develop technology to allow optimum low-emission combustion systems to be designed and widely used by industry.

3.3.2 Advanced Combustion Modification Techniques

Aerotherm Division of Acurex Corporation is conducting a 2-year IERL-RTP funded pilot-scale furnace test program to develop advanced combustion control techniques for NO_x reduction. The test furnace, with a capacity of

3,165,000 KJ/hr (3,000,000 Btu/hr) is being operated in the wall-fired and tangential, corner-fired modes and is capable of firing coal, oil, gas, mixed fuels, waste fuels, and synthetic fuels from coal. The furnace was designed to give a temperature/time profile of the combustion gases representative of industrial and utility boilers providing for more direct translation of low NO_x firing configurations to full scale equipment. The results of this program will guide demonstration tests on large-scale prototype units and provide suggestions for advanced equipment design. Preliminary baseline, uncontrolled tests showed very good correspondence with full-scale equipment with both the level of NO_x emission and the trend with excess air and preheat. Emphasis to date in the NO_x control development tests has been on optimizing procedures for staging by use of overfire air ports with the firing of pulverized coal in the wall-fired mode. Variables considered in the optimization tests include first-stage stoichiometry and mixing, first and second stage stoichiometry, overfire air preheat and injection pattern, total excess air and burner air preheat. Tests with a high nitrogen Kentucky bituminous coal have shown NO_x reductions in excess of 75 percent when the primary flame zone is operated with 90 percent or less of stoichiometric air. At a total excess air level of 15 percent, NO_x emissions are in the range of 100 to 200 ppm (corrected to zero percent O_2) with staged combustion compared to a level of 850 ppm with normal, uncontrolled operation. These optimization tests are being extended to the firing of other coal types and to operation in the tangential firing mode.

Rocketdyne Division of Rockwell International under IERL-RTP contract has recently completed a two-part study which resulted in the development of an advanced design residential warm air oil furnace which offers a 65 percent reduction in NO_x emissions and up to 10 percent increase in fuel efficiency. The initial effort involved the development of an optimal oil burner head through evaluation of the effects on NO_x formation of combustion air, swirl angle, nozzle spray angle, axial injector placement, flue gas recirculation, and combustion gas recirculation as a function of oil flowrate and overall excess air. The optimized burner was a nonretention gunburner with an optimized choke-diameter and swirl vanes. Hydrocarbon and CO emissions remained at commercial burner baseline levels while NO_x emissions were 1 g NO/kg fuel

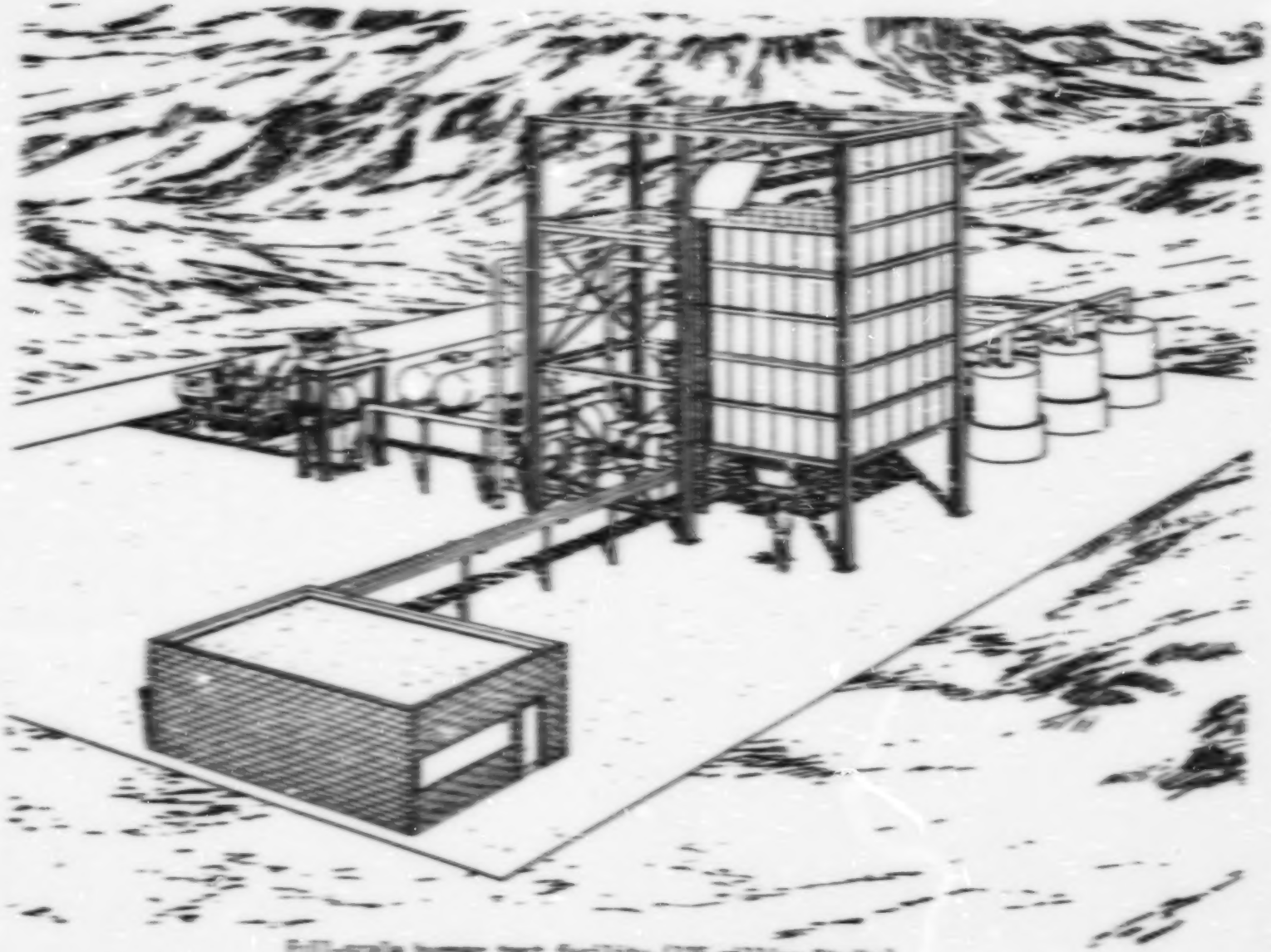


Multiburner experimental furnace (3 million Btu/hr)

compared to 2 to 3 g NO/kg fuel at baseline. The second part of the program was directed toward development of an optimized burner/firebox combination. The final design utilized the optimized burner firing into the side of a vertical, cylindrical, fin-cooled firebox. At 10 percent excess air, NO_x emissions of 0.6 g NO/kg fuel were measured and increases in system efficiency of up to 10 percent have been experienced. The system has recently completed a 500-hour lab performance test and will be ready for field testing in the near future. In addition to system development, the program has evaluated techniques for mass production of the optimized head. A final report is scheduled for completion in late 1976. A new contract has recently been signed with Rocketdyne to extend the previous study to the investigation of feasible manufacturing processes for the new oil furnace designs. This contract calls for the manufacture of six units for use in field tests during the 1977 to 1978 heating season.

A contract has recently been awarded to Honeywell for an experimental study to investigate the characteristics of fuel oil atomization with a thermal aerosol oil burner using #1 and #2 fuel oils with emphasis on combustion efficiency, soot formation and design requirements. The effect of oil temperature and pressure, droplet size, inlet air temperature, air/fuel ratio and firing rate on flame luminosity, soot particle concentration and size distribution, NO_x emissions and flue gas temperature will be investigated. Additional measurements will be taken of CO, HC, smoke, O_2, CO_2, stack temperature and burner efficiency.

Ultrasystems, Inc. is under contract to IERL-RTP to define low NO_x burner design criteria for scale-up from an experimental 5 million Btu/hr optimized burner to practical size burners (125 million Btu/hr). The scaling criteria will assess the burner interactions occurring on full-scale boilers. The emphasis is on coal burners, although residual oil and combined coal/low Btu gas are also to be studied. The burner test facility was designed to allow evaluation of the performance of single burners of capacity up to 125 million Btu/hr and multiple burners totaling 60 million Btu/hr in combustion chambers simulating commercial practice. The facility has been completed, and tests are scheduled for an early 1977 start date.



Full-scale burner test facility (125 million Btu/hr)

Ultrasystems is also conducting a study to generate low emission burner concepts for residual oil combustion in packaged boilers. The study consists of an experimental phase (for the development of burner design concepts applicable to package boiler geometry) and an application phase (for testing a prototype burner in a field operating boiler). To date, a variety of burner configurations have been studied and an optimum has been identified which gives NO_x reductions in the range of 65 to 75 percent for three fuel oils with nitrogen content between 0.2 and 0.71 percent. The 0.2 percent nitrogen produced the lowest NO_x (120 ppm) while maintaining acceptable smoke levels. The results have also identified oil atomization conditions and fuel properties as important variables governing both NO_x and smoke levels. A contract is under negotiation to investigate these parameters as related to combustion air flow patterns.

3.3.3 Catalytic Combustion

Aerotherm has recently been contracted by IERL-RTP to investigate the concept of catalytic combustion in which premixed clean fuels are reacted heterogeneously and at low temperature over catalytic monoliths. The overall objective of the program is to provide scale-up criteria to allow application to a wide range of stationary combustion equipment. The objective will be met by screening small scale catalysts, performing small scale system concept tests, and then scaling the results up to larger catalysts and systems. Results of the small-scale catalyst screening experiments have identified the graded-cell catalyst system as an acceptable concept for futher testing. The graded-cell system uses a ceramic monolith with large cells at the combustion inlet, with subsequent monolith sections having progressively smaller cells. The catalyst used is platinum or an alumina washcoat. Tests with this system have shown good performance under lean conditions with both methane and propane fuels.

3.3.4 Alternate Fuels

Past in-house work has led to significant understanding of the formation and control of fuel NO produced from chemically-bound nitrogen. The study has examined burner design, staged combustion, flue gas recirculation,

and other techniques for control of both thermal and fuel NO from natural gas, propane, distillate and residual oils, and coal. The current thrust of this program is to define combustion and emission characteristics of alternate fuels, with emphasis now being placed on high-nitrogen coal-derived fuels. The program makes use of a versatile 3C9,000-Btu/hr experimental furnace with provision for precise control of combustion parameters such as fuel type and injection method, air rate and introduction method, air preheat, firebox residence time, and firebox and convective section heat removal rate. In addition, combustion modification techniques can be studied in a variety of applications. The initial class evaluated was alcohol fuels, which may be produced from coal gasification. They appear to have low emissions of NO and favorable combustion characteristics relative to conventional clean fossil fuels. The next class of fuels to be studied will be low-Btu gas. A fuel gas generator has been designed and built by the Jet Propulsion Laboratory under an interagency agreement and will be delivered in late 1976. The key process variables will be $CO/H_2/N_2$ ratios, fuel gas temperature, and NH_3 content.

3.4 FUNDAMENTAL STUDIES

IERL-RTP's fundamental research studies are providing an understanding of the important phenomena in the formation and destruction of pollutants during combustion. The basic knowledge is being translated to pilot scale or field equipment studies to identify how the pollutant formation mechanisms can be controlled through combustion process modifications. The primary purpose of this program element is the application of fundamental research to practical NO_x control problems with emphasis on interpretation of test data, identification of further test programs, understanding and resolving operational problems, and suggestion of new research areas. A contractor will soon be selected to perform and subcontract a highly coordinated fundamental studies effort to consolidate the present programs. Program efforts will focus on application to field and pilot scale test results. Fundamental studies fall into two categories: combustion chemistry and combustion aerodynamics. Combustion chemistry is a complex process involving both fuel decomposition reactions and reactions of other flame species re-

Figure 14. Operator adjusting the Video Tool Control

sulting in formation and destruction of pollutant species. The pollutant species of interest are NO_x, CO, HC, POM, carbon particulate, fuel ash, and SO_x. The emphasis in this program is on NO, although the formation and destruction of other oxides and reduced nitrogen species (e.g., HCN and NH_3) are also included.

3.4.1 Combustion Chemistry

The area of combustion chemistry can be further subdivided into two areas: pollutant formation related to combustion conditions, and pollutant formation related to fuel composition. These areas are reflected in the characterization of NO_x formed by fixation of atmospheric nitrogen at high temperature in the combustion process as thermal NO_x, and that formed from oxidation of nitrogen chemically bound in solid and liquid fossil fuels as fuel NO_x. For most fuels the total NO_x is the composite formed by both mechanisms.

A new experimental program has recently been awarded to United Technology Research Center for investigation of nitrate and sulfate formation and NO_x/SO_x interactions in flat flames in which various dopants will be used to promote formation of these species. Tests will be conducted to determine the extent of *in situ* probe interference on NO_x measurements in flames. A variety of measurement techniques will be used in this determination including microprobes, and optical and molecular beam mass spectroscopy. The data gained on inflame species concentrations will then be used to determine respective formation mechanisms through use of the PROF computer program described below.

A computer program has been developed at Aerotherm to analyze combustion and pollutant chemistry in premixed flat flames. The Premixed One-Dimensional Flame (PROF) code is a powerful tool being used to isolate governing kinetics by comparison to experimental data from past and ongoing flat flame measurements. PROF has the capability of handling multicomponent diffusion, heat loss and wall effects characteristic of real flames. The systematic comparison of data and suggested kinetics is revealing the governing mechanisms of pollutant formation and destruction including those of inorganics and fuel nitrogen. Successful utilization of the PROF code will demonstrate the strong coordination between the experimental and analytical activities in fundamental studies.

Rockwell International's Rocketdyne Division is working, under an IERL-RTP contract, to establish the mechanism and chemistry of fuel nitrogen conversion to NO_x and other products. An experimental and analytical study has been carried out to investigate the chemical mechanisms involved in the conversion of fuel nitrogen to NO_x in combustion as a means of developing new approaches for minimizing fuel nitrogen conversion. The experimental work was composed of two portions: (1) pyrolysis reactions that the volatile fuel nitrogen compounds will undergo before approaching the flame front, and (2) combustion reactions of fuel nitrogen compounds and their reaction products. Pyrolysis experiments were conducted with model fuel nitrogen components, to measure the kinetics parameters that determine under what conditions typical fuel nitrogen structures will decompose and to identify the nitrogen-containing species that are formed. Common fuel nitrogen structures were represented by the model compounds pyridine, pyrole, quinoline, and benzonitrile. Fuel oils and coals were subsequently pyrolyzed under similar conditions, and the nitrogen containing inorganic products were measured and compared with those formed by the model compounds. Results indicate that HCN is a likely important intermediary compound in the formation of fuel NO_x from fuel bound nitrogen in combustion. Burner studies of fuel NO_x reaction paths induced by the addition of HCN and NH_3 to premixed CH_4-O_2-Ar flames were also conducted to determine the kinetics of NO formation from these intermediaries. Results indicate that fuel NO forms relatively slowly above the luminous zone in the same region where CO is oxidized to CO_2 or after. Results also indicate that NH_3 may yield HCN as an intermediary in the reaction to form NO. High NO yields were found with lean flames and low NO yields, with rich flames. A one-dimensional mathematical kinetic-diffusion model for the combustion of oil droplets and coal particles was developed to simulate the thermochemistry controlling the formation of fuel NO_x. The model is being used in a continuing effort to define the mechanisms and chemical paths leading to fuel NO_x. This contract has been extended to consider the pyrolysis of additional nitrogen containing fuels and pure compounds under oxidation conditions and further to explore the interactions of thermal and fuel NO_x formation mechanisms in flames.

MIT, under IERL-RTP sponsorship, is investigating the formation of soot and polycyclic aromatic hydrocarbons (PCAH) in combustion systems.

The objective of the study is the assessment of the production of particulate organic matter (soot and organic compounds) in well-defined yet relevant combustion systems. Tests are being conducted on both laminar and turbulent atmospheric diffusion flames. Acetylene-oxygen laminar flat flame tests will be conducted at full equivalence ratios and burner exit velocities, and data will be taken on species concentrations, temperature profiles, and particle concentration and size distribution as a function of position in the flame. A water-cooled sampling probe will produce data on mass loadings of soot, number concentration, and size distribution of soot and concentrations of PCAH species in the turbulent diffusion flame. The apparatus is capable of burning either liquid or gaseous fuels with variation of equivalence ratios and full injection modes. Preliminary runs at an equivalence ratio of 1.0 showed a 4 order of magnitude increase in exhaust gas soot loading with a decrease in atomizing air pressure from 20 to 10 psig. This illustrates the extreme sensitivity of soot emissions and possibly PCAH emissions to changes in combustor firing practices in an effort to reduce NO_x.

Further grant studies by MIT on the fate of coal nitrogen during pyrolysis and oxidation are now in progress. The overall objective of this study is the determination of the distribution of fuel nitrogen between char and volatiles and the fate of the char and volatiles under simulated combustion conditions. Tests are conducted on a controlled atmosphere isothermal furnace from which pyrolysis or oxidation products are withdrawn with a water-cooled probe. Long residence times are simulated by allowing the coal particle to free fall through the furnace, and short residence times require a high preheated gas flowrate. A swelling bituminous coal and a nonswelling lignite of fuel nitrogen content 1.04 and 0.51 percent, respectively, have been selected. Preliminary data indicate that: (1) fuel nitrogen devolatization is kinetically controlled, (2) significant amounts of nitrogen (about 70 percent at 1750°K) may remain in the char after devolatization, (3) NO formation decreases with increasing fuel/air equivalence ratios, and (4) as much as 40 percent of the nitrogen may remain in the char at fuel/air equivalence ratios greater than 1.5. From these findings, current data indicate that nitrogen in the char may contribute significantly to NO_x emissions at temperatures below 1750°K but less at higher temperatures.

Under an IERL-RTP grant, the University of Arizona is conducting an experimental program to study the potential impact of fuel desulfurization on the formation of NO_x emissions. Laboratory flat flame experiments showed that the presence of sulfur may inhibit the formation of thermal NO_x. Data were inconclusive in establishing a relationship between fuel sulfur and fuel nitrogen conversion to NO_x. Further tests are presently being run on a larger furnace with swirling flames. These tests utilize dopants for both nitrogen and sulfur compounds in oil flames.

3.4.2 Combustion Aerodynamics

Although combustion chemistry is responsible for the formation and destruction of pollutants, the actual conditions that exist in the flame zone are a strong function of the physical processes of combustion. Most practical combustors operate with diffusion flames where the fuel and air are introduced separately and mixing depends on the manner of introduction.

The flame zone is not of homogeneous composition; therefore, it is necessary to understand the role of combustion aerodynamics in pollutant formation.

United Technology Research Center is under contract to IERL-RTP to investigate the interaction of aerodynamics and combustion chemistry (in an idealized single burner combustor) as a function of fuel type and various inlet parameters. During this study, detailed mapping of the local chemical composition, temperature, velocity, and turbulence profiles is being accomplished. Initial studies, using *in situ* probes, investigated air preheat, stoichiometry and flame swirl. Further testing utilizing a laser-doppler-velocimeter (LDV) has recently been completed on gas and liquid fuel flames. The LDV allows for the determination of turbulent flame structure without probe interference, and it measures turbulence level as well as mean velocity. Tests using the LDV on gas and liquid flames investigated the effect of swirl, fuel/air velocities and pressure level on the flow and NO_x formation. Results showed that large scale turbulence was dominating both combustion and pollutant formation. These results indicate a need to identify the interaction of turbulence reaction kinetics within the flow field. Optical methods were utilized to measure the liquid spray characteristics from the injection of propane, iso-octane, and distillate oil. The results yielded good data on

spray pattern, velocity profiles and droplet particle spacing. Reports on the UTRC experimental studies are due out soon. The UTRC experimental program is part of a coordinated experimental/analytical program to produce tools with which to evaluate practical test results. The analytical portion of the UTRC program is investigating the use of flow field computations to describe recirculating combustion flow. In addition, UTRC has been working to improve a computer code for rigorous solution of the Navier-Stokes flow equations. The major effort has been on improving the turbulence model and comparing model predictions with cold-flow and hot-flow furnace data. To date, simple chemical kinetics have been used. The strong influences of boundary conditions in general and of radial inlet profiles in particular on predictions have been demonstrated. It appears that advances in numerical differencing techniques will be needed before a generally applicable method can be used to develop a simplified treatment of combustion chemistry and aerodynamics.

3.4.3 Application for Combustion Control

A contractor is being selected to plan and execute a 3-year effort to integrate the results of prior and ongoing fundamental studies and initiate new studies of combustion and combustion generated air pollution. The new program, scheduled for an early 1977 startup, will consolidate the diverse fundamental studies projects into one large highly-coordinated program whose efforts will be focused on application to field and pilot scale test results. The control program has progressed to the stage where preferred approaches to NO_x control have been well defined. Consequently, the fundamental studies program is being structured to focus on needs in data interpretation, generation of new R&D directions, and operational problems.

APPENDIX A

EPA/IERL-RTP REPORTS ON NO_x COMBUSTION MODIFICATION

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EPA/IERL-RTP REPORTS ON NO_x COMBUSTION MODIFICATION

The following reports funded by EPA/IERL-RTP or predecessor components were published before December 1976:

EPA No.	NTIS No. (PB)	Report
APTIC 15568	186-234	"Fluid Bed Studies of the Limestone Based Flue Gas Desulfurization Process", Esso (10/68).
APTIC 12619	184-479	"Systems Study of NO_x Control Methods for Stationary Sources, Interim Report", Esso (5/69)
APTD 1286	192-789	"Systems Study of NO_x Control Methods for Stationary Sources, Volume II, Final Report", Esso (11/69).
---	---	"Models for NO Formation in Combustion Processes", MIT (7/69-10/70).
APTIC 28287	---	"Reduction of Air Pollutants from Gas Burner Flames Including Related Reaction Kinetics", U.S. Bureau of Mines (1970).
APTD 1266	189-076	"Residual Fuel Oil-Water Emulsions", Battelle (1/70).
AP 87	213-630	"Effects of Fuel Additives on Air Pollutant Emissions from Distillate-Oil-Fired Furnaces", EPA Control Systems Laboratory (IERL-RTP) (6/71).
APTD 0924	207-110	"Systematic Study of Air Pollution from Intermediate-size Fossil Fuel Combustion Equipment", Walden Research (7/71).

EPA No.	NTIS No. (PB)	Report
APTD 1163	210-739	"Systematic Field Study of NO_x Emission Control Methods for Utility Boilers", Esso (12/71).
EPA-650/ 2-74-017	230-095/A5	"Kinetic Mechanisms Governing the Fate of Chemically Bound Sulfur and Nitrogen in Combustion", Shell Development (8/72).
EPA-R2-72-078a	213-297	"State of the Art for Controlling NO_x Emissions, Part 1: Utility Boilers", Catalytic, Inc. (9/72).
APTD 1160	211-480	"Laboratory Studies and Mathematical Modeling of NO_x Formation in Combustion Processes", Esso (1972).
EPA-R2-73-210	221-457	"Stationary Internal Combustion Engines in the U.S.", Shell Development (4/73).
EPA-R2-73-192	226-294	"Systems Study of Conventional Combustion Sources in the Iron and Steel Industry", Walden Research (4/73).
EPA-R2-73-084a, b	223-148	"Field Investigation of Emissions from Combustion Equipment for Space Heating", Battelle (6/73).
EPA-R2-73-291	223-003	"Nitric Oxides Formation in Combustion Processes with Strong Recirculation", United Aircraft (7/73).
EPA-R2-73-292a	224-274/A5	"Experimental Combustor for Development of Package Boiler Emission Control Techniques", Ultrasystems (7/73).
EPA-650/ 2-73-018	223-002	"Catalytic Combustion, A Pollution-Free Means of Energy Conversion?", EPA Control Systems Laboratory (IERL-RTP) (8/73).
EPA-650/ 2-73-014	224-424/A5	"Investigation of Surface Combustion Concepts for NO_x Control in Utility Boilers and Stationary Gas Turbines", Aerospace (8/73).

EPA No.	NTIS No. (PB)	Report
EPA-650/ 2-73-005	226-547/AS	"Program for Reduction of NO_x from Tangential Coal-Fired Boilers", Combustion Engineering (8/73).
EPA-650/ 2-73-029	224-208	"Interactions of Stack Gas Sulfur and Nitrogen Oxides on Dry Sorbents", EPA Control Systems Laboratory (IERL-RTP) (9/73).
EPA-650/ 2-73-021	224-210/AS	"Proceedings, Coal Combustion Seminar, June 19-20, 1973", EPA Control Systems Laboratory (IERL-RTP) (9/73).
EPA-650/ 2-73-031	225-037/1AS	"Effectiveness of Selective Fuel Additives in Controlling Pollution Emissions from Residual Oil-Fired Boilers", EPA Control Systems Laboratory (IERL-RTP) (10/73).
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EPA-650/ 2-74-026	237-355/AS	"Investigation of Particulate Emissions from Oil-Fired Residential Heating Units", Battelle (3/74).
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EPA-650/ 2-74-038	233-037/AS	"Combustion Control of Pollutants from Multiburner Coal-Fired Systems", U.S. Bureau of Mines (5/74).
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EPA-650/ 2-74-047	236-647/AS	"Design of an Optimum Distillate Oil Burner for Control of Pollutant Emissions", Rockwell Int. (Rocketdyne) (6/74).
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EPA-650/ 2-75-002b	241-283/AS	"Effects of Design and Operating Variables on NO_x from Coal-Fired Furnaces, Phase II", Babcock and Wilcox (2/75).
EPA-650/ 2-74-023	241-780/AS	"Evaluation of Prechamber Spark Ignition Engine Concepts", Aerospace (2/75).
EPA-650/ 2-75-017	241-821/AS	"Identification and Characterization of the Use of Mixed Conventional and Waste Fuels", M.W. Kellogg (2/75).
EPA-650/ 2-75-046	241-911/AS	"Evaluation of Low Sulfur Western Coal Characteristics, Utilization, and Combustion Experience", Monsanto (5/75).
EPA-650/ 2-73-005a	245-162/AS	"Program for Reduction of NO_x from Tangential Coal-Fired Boilers, Phase II", Combustion Engineering (6/75).
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EPA-650/ 2-73-005b	246-089/AS	"Program for Reduction of NO_x from Tangential Coal-Fired Boilers, Phase IIa, NO_x Control Technology Application Study", Combustion Engineering (8/75).
EPA-600/ 2-75-048	246-750/AS	"NO_x Combustion Control Methods and Costs for Stationary Sources", Aerotherm (9/75).
EPA-600/ 2-75-075	248-099/AS	"Effect of Fuel Sulfur on NO_x Emissions from Premixed Flames", University of Arizona (10/75).

EPA No.	NTIS No. (PB)	Report
EPA-600/ 2-75-069a	248-292/AS	"Guidelines for Residential Oil-Burner Adjustments", GPO Stock No. 055-003-00085-8, Battelle (10/75).
EPA-600/ 2-76-003	248-139/AS	"Survey and Evaluation of Kinetic Data on Reactions in Methane/Air Combustion", Exxon (1/76).
EPA-600/ 2-76-039	250-373/AS	"Chemistry of Fuel Nitrogen Conversion to Nitrogen Oxides in Combustion", Rockwell Int. (Rocketdyne) (2/76).
EPA-600/ 2-76-030	250-078/AS	"Residential Oil Furnace System Optimization", Rockwell Int. (Rocketdyne) (2/76).
EPA-600/ 2-76-037	252-195/AS	"Catalytic Oxidation of Fuels for NO_x Control from Area Sources", Aerotherm (2/76).
EPA-600 2-76-068	251-919/AS	"Guidelines for Burner Adjustments of Commercial Oil-Fired Boilers", Battelle (3/76).
EPA 600/ 2-76-086a	253-500/AS	"Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers, Phase II", KVB Engineering (4/76).
EPA-600/ 2-76-098a	254-167/AS	"Burner Design Criteria for Control of NO_x from Natural Gas Combustion, Volume I", Institute of Gas Technology (4/76).
EPA-600/ 2-76-152a	256-320/AS	"Proceedings of the Stationary Source Combustion Symposium, Volume I, Fundamental Research", EPA/IERL-RTP (6/76).
EPA-600/ 2-76-152b	256-321/AS	"Proceedings of the Stationary Source Combustion Symposium, Volume II, Fuels and Process Research and Development", EPA/IERL-RTP (6/76).

EPA No.	NTIS No. (PB)	Report
EPA-600/ 2-76-152c	257-146/A5	"Proceedings of the Stationary Source Combustion Symposium, Volume III, Field Testing and Surveys", EPA/IERL-RTP (6/76).

APPENDIX B

CONVERSION FACTORS

To Convert from:	To	Multiply by:
tons	kilograms	9.07×10^{2}
inch	meter	2.54×10^{-2}
pounds/hour	kilogram/second	1.26×10^{-4}
gallons/hour	meter^3/second	1.05×10^{-6}
horsepower (boiler)	watts	9.81×10^{3}
Btu/hour	watts	2.93×10^{-1}
pounds/square inch	pascal	6.89×10^{3}